Figure 76 shows a block diagram of the PET-2A process. Six types of input data are required. They are:

1. Signal level at the output port of a receiving antenna from a propagation prediction program.
2. The signal-to-noise ratio required for the reception of a chosen modulation format.
3. The loss of signal (if any exists) in the RF-Distribution System (RFD) of a site.
4. Any increase in the noise floor at the input terminals of a receiver due to RFD components. This is expressed in dB over the design noise floor of the site, and usually measured in a 3-kHz Gaussian-shaped bandwidth.
5. The level of man-made noise, expressed in dB over the design noise floor of the site, is usually measured in a 3-kHz Gaussian-shaped bandwidth.
6. Attenuation at the input stage of a receiving system introduced to limit receiver saturation caused by strong signals.

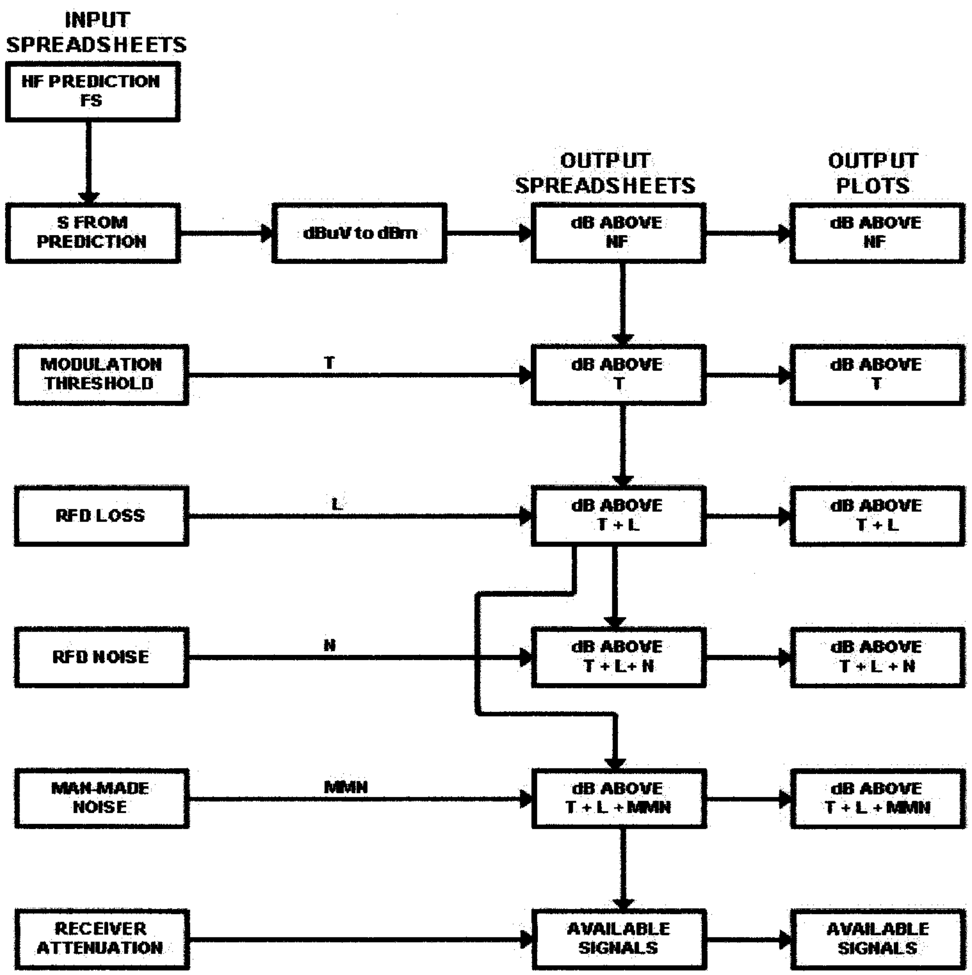

Figure 76 Block Diagram of PET-2A

Figure 76 uses a number of abbreviations to minimize the amount of text in each block. These abbreviations are:

FS	Signal Strength module of PROPHET or other similar program.
S	Signal strength at the antenna output in dBµV.
RFD	Radio-Frequency Distribution System of a site.
NF	Noise floor in dBm.
T	Detection threshold of the modulation of the signal of interest.
L	RFD loss.
N	Noise added by RFD components.
MMN	Man-made noise in dB above the NF.

For the primary use of PET-2A, these parameters are provided at each hour of the day and in frequency increments of 1 or 2 MHz over the 2- to 30-MHz band. Closer frequency and time intervals can be used for special analysis cases. All of the listed parameters must be obtained to evaluate the impact of each on signal reception.

The operation of PET-2A is described by a number of sequential steps.

Step 1.

Obtain the operating parameters and location of the signal-source and the receiver sites. Enter these parameters into the FS module of PROPHET Version 5.1 or other propagation program along with the desired date and the sunspot number or other equivalent measure of radiation from the sun. Compute the strength of the SOI at the output terminals of the receiving site's antenna in dBµV. Convert the dBµV values into dBm and enter the dBm values into the spreadsheet labeled "S" from PROPHET.

This will produce Output 1. The values in Output 1 represent signal levels at the output port of the antenna. The values shown are signal strength above the site's design noise floor for a 0-dB (S+N)/N ratio. The 3-axis view shows signal levels for a 24-hour period.

Step 2.

Enter the modulation threshold required to obtain good reception of the particular type of modulation employed. PET will automatically produce the second output. Output 2 shows the signal level above the threshold level for the type of modulation used by the SOI. This plot represents the best the site can accomplish. The values of Maximum Usable Frequency (MUF) and the Lowest Useful Frequency (LUF) are established by the propagation path, and site parameters will not significantly affect these values.

Step 3.

Enter the signal loss between the antenna and the receiver. In a well designed site this value will be very low. The signal loss can be significant in a modified site. Signal loss values will probably not change with time of day. Enter the measured values in the first column of the spreadsheet and copy these values to all other times of the day.

Step 4.

Enter the amount of noise appearing at the input to a site's receiving system that exceeds the design noise floor of the site. A 3-axis plot will appear at Plot 4. This plot will show the signal level at the input to a site's receiver after RFD loss and RFD noise floor effects are considered.

Step 5.

Enter the man-made noise levels. These levels will change from hour to hour, from frequency to frequency, and with the activity of the noise sources. Erratic jumps in noise can occur. Enter the actual data. A 3-axis plot will appear as Plot 5. This plot shows detectable signals that exceed the modulation-detection threshold, RFD loss, RFD noise, and man-made noise.

Step 6.

Some receivers have an attenuator prior to their first stage. This attenuator is used to reduce strong signals to harmless levels and to avoid excessive intermodulation production. If the receiver of interest has such an attenuator, record its value at hourly intervals and enter the values into the spreadsheet labeled "Receiver Attenuation." A 3-axis plot will appear as Plot 6. This plot will show all detectable signals that exceed the modulation threshold, RFD loss, man-made noise, and receiver attenuation.

Select the desired output plots. Usually Plots 2 and 5 or 6 will be sufficient for an overall analysis of the ability of the site to receive SOI. Prior to printing the plots, manually remove all negative values of signal from each output spreadsheet. Negative values represent signals below the detection threshold which cannot normally be received.

Should the impact of a specific factor, i.e. RFD loss, be of interest, then Plots 2 and 3 will provide the degradation in signal detection from that factor. Other combinations of output plots will provide information about the extent of degradation of receiving capability from other factors.

A numerical evaluation of the loss in receiving capability can be obtained by counting the frequency-time blocks in each view. While the 3-axis plots provide an excellent overall view of the operation of a receiving site, the data in some frequency-time blocks can obscure data in other blocks. The maximum value of the amplitude scale of any plot can be manually increased to a higher value up to 999 dB. This compresses the amplitude-time blocks and allows them to be viewed and counted.

Keep in mind that the source of signal levels, the FS module in PROPHET Version 5.1, calculates the average monthly signal values. Signals that are both above and below the calculated values will appear at the antenna output terminals. In addition, PET-2A should be used to evaluate signal reception only during periods of low magnetic-storm activity, and no solar flares. This can be determined by monitoring the magnetic activity and sunspot values provided by WWV and other time-standard stations. The same kind of information is available from the Internet[5].

While a number of propagation prediction programs are available to provide information about the signal path between a source and a receiving site, the program "Advanced PROPHET" developed by the Naval Ocean Systems Center, San Diego, CA was used for the examples in this document. PROPHET provides a plot of average hourly diurnal values of the Maximum Usable Frequency (MUF), the Lowest Useful Frequency (LUF), and the Frequency of Optimum Transmission (FOT). In addition PROPHET provides tables of the hourly average signal level

---

[5] http://wdc-c2.crl.go.jp.ISD/index-E.html or
http://solar.spacew.com/www/realtime.html

expected to be delivered by the receiving antenna to the site's Radio Frequency Distribution (RFD) system.

Most PET-2A tasks subsequent to the production of the examples shown in this document have used the Proplab-2 prediction program. This program provides a means to use near real time ionospheric parameters as well as non-great circles modes of propagation. Since the distribution of the PROPHET program is limited and the program is not being updated and maintained, new users might find the Proplab-2 program to be more suitable.

B.2 AN EXAMPLE OF PET-2A

The first step in the use of PET-2A is to select candidate locations for a few signal sources and to determine the primary properties of each source. Table 1 shows the properties of a source labeled as Source 1. This source was being received at the receiving site being evaluated. The source characteristics are as follows:

Identification Symbol	TEST 1
Latitude	
Longitude	
Antenna	$\lambda/2$ Dipole
Power	1000 Watts
Modulation	3-kHz digital modulation
Distance	3900 km
Coverage Area	Primary

Next, a propagation prediction program is used to determine the average values of the Maximum Useable Frequency (MUF) and the Lowest Useful Frequency (LUF) for each hour of the day on the path from the source to the receiving site along with the average values of hourly received signal strengths. Ionospheric conditions for the date of the investigation were used for the production of the examples. This date was the nearest mid-month date to the accumulation of site data. Actual values of man-made radio noise obtained during a 24-hour measurement period at the receiving site were used in the analysis.

Figure 77 provides a listing of the hourly signal strengths in 2-MHz increments of frequency across the entire HF band. This data is used as the first input into the PET-2A program.

```
*** UNCLASSIFIED ***
DATE:  9/ 9/2000      ATMOSPHERIC NOISE: NO
10.7 CM FLUX: 160.0   X-RAY FLUX:   .0010   MAN-MADE NOISE: QM
CC           LAT:           LON:          ANT: 101 @ *OMNI* PWR:     1000.00
ROTA         LAT:           LON:          ANT: 666 @ *OMNI* RANGE:   3894 KM

              SIGNAL STRENGTH  (DB ABOVE 1 MICROVOLT)

                            FREQUENCY
TIME 2        8          16          24          32          40   LF MF
00  20 26 26 29 32 33  5                                           2 12
01  20 26 26 29 32 18-17                                           2 11
02  20 26 26 29 24-12                                              2 10
03  20 26 26 29 14                                                 2  9
04  20 26 26 29 32 33 34 35 35  9                                  2 18
05 -17 11 20 22 26 30 32 33 34 35 31 14-17                         2 23
06         4 16 22 25 27 31 32 34 29 25 19 -8                      4 26
07            1 16 21 23 26 30 32 28 24 21 14-14                   5 28
08           -9 10 16 20 24 26 31 27 23 21 20  0                   6 29
09              -1 13 18 22 24 30 26 22 20 20  9-18                6 29
10              -4 11 16 20 23 26 25 21 19 19 12-14                7 30
11              -5 10 15 20 23 25 25 21 19 19 12-14                7 30
12              -5 11 16 20 23 26 25 21 19 19  8-18                7 29
13              -2 12 17 21 24 29 26 22 20 19  1                   6 29
14          -11  9 15 19 23 25 30 26 22 20 20-10                   6 28
15           -2 14 19 22 25 30 32 28 23 21  3                      5 27
16        -1 13 20 23 25 30 32 33 29 24 11-17                      4 25
17     -7 17 20 25 29 31 32 33 35 30 15-15                         3 23
18  12 24 25 28 31 32 33 34 35 36 11                               2 21
19  20 26 26 29 32 33 34 35  5                                     2 16
20  20 26 26 29 32 33 34  9                                        2 14
21  20 26 26 29 32 33 21-10                                        2 13
22  20 26 26 29 32 33 20-11                                        2 13
23  20 26 26 29 32 29 -3                                           2 12
FS>
```

Figure 77 Average Values of Received Signals for the Test Case

The above values are converted into dBm for a 50-Ohm load and entered into Spreadsheet 1. These values represent the average signal strength obtained at the output terminals of an omi-directional antenna located at the receiver site.

Next the modulation detection threshold of the receiving system is entered into Spreadsheet 2. This is the signal margin above noise needed to detect the received signal and provide a low error copy of the modulation of that signal.

In this case, the receiving site contained cable loss between the antenna and the receiver. This loss was measured and entered into Spreadsheet 3.

In some cases, additional radio noise is generated by components between the antenna and the receiver. Thus, the noise at the input terminals of a receiver is measured with the antenna removed from the site's signal-distribution system and replaced with a suitable termination. This noise level is entered into Spreadsheet 4

The man-made radio-noise values at the antenna terminals are measured in two-hour increments over a 24-hour period, and these values are entered into Spreadsheet 5. In this case the external noise was entirely from sources on distribution power lines that were within line of sight of the uppermost part of the antenna used for reception. The sources varied in distance from the site's antenna from 1 km to more than 10 km. During this measurement some erratic variations in noise level were noted because of changes in the activity of sources. The level at the time of the measurement was used rather than the peak or minimum noted between measurement times

Finally, some receivers contain an attenuator at their input to limit the maximum signal level. This is done to prevent overloading the receiver with the resultant loss of linearity and the introduction of intermodulation products and intermodulation noise. The receiver used for this analysis did not contain such an attenuator.

Figure 78 provides an example of the measured man-made noise levels for the site. In this case the levels are expressed in dB above -130 dBm where -130 dBm is the minimum signal-detection level for the specific receiver used in the analysis when it used a 3-kHz signal-detection bandwidth.

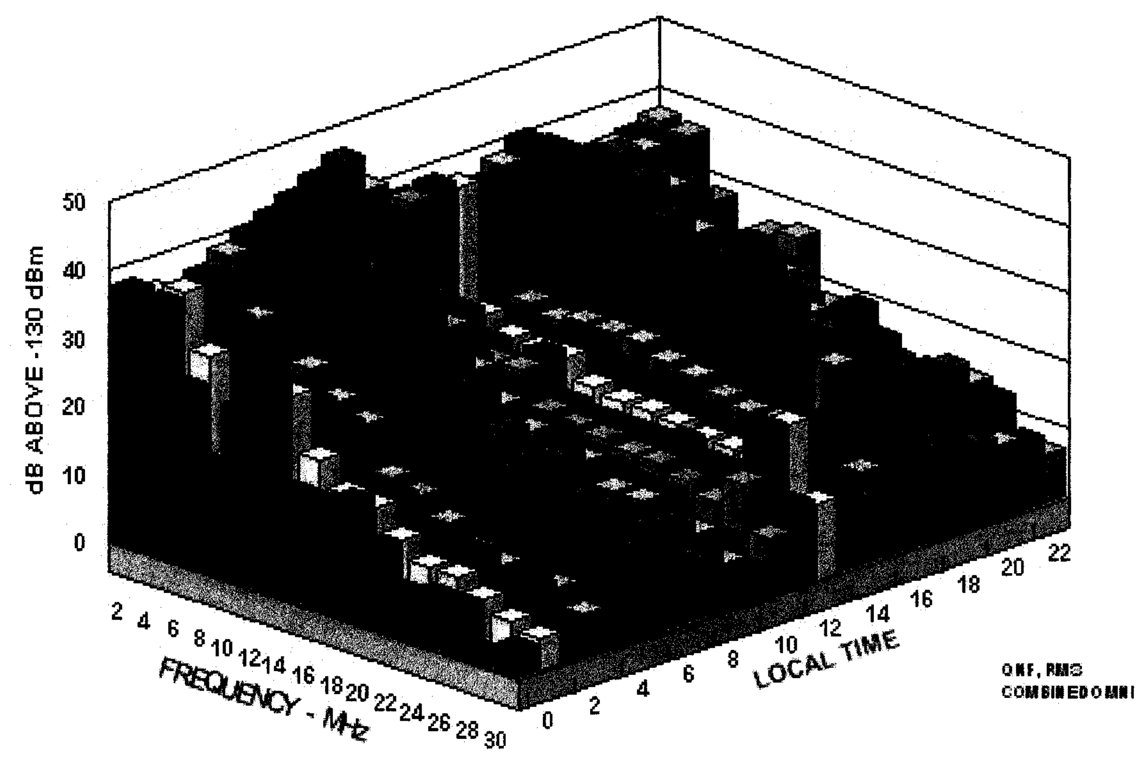

Figure 78 Radio Noise Levels at the Antenna Output Terminals

Output 1 of the PET-2A program provides an overview of the signal strengths available at the antenna terminals where the amplitude scale is in dB above -130 dBm. This output illustrates the ability of the site to detect signals under perfect site conditions with no signal-distribution loss, no signal-distribution noise, a 0-dB modulation-detection margin, and no man-made radio noise. Figure 79 shows a plot of predicted received signal levels for the source selected and at the year and season of the measurement.

The impact of the ionosphere on signal propagation is evident in this example. The diurnal changes in the MUF and LUF are prominent aspects of the example along with the impact of path absorption on signal strength. In this case a few signals would be received at frequencies above the upper limit of the HF band during the mid afternoon hours. Signals would also be received from the source at frequencies below the lower limit of the HF band after midnight and during the early morning hours.

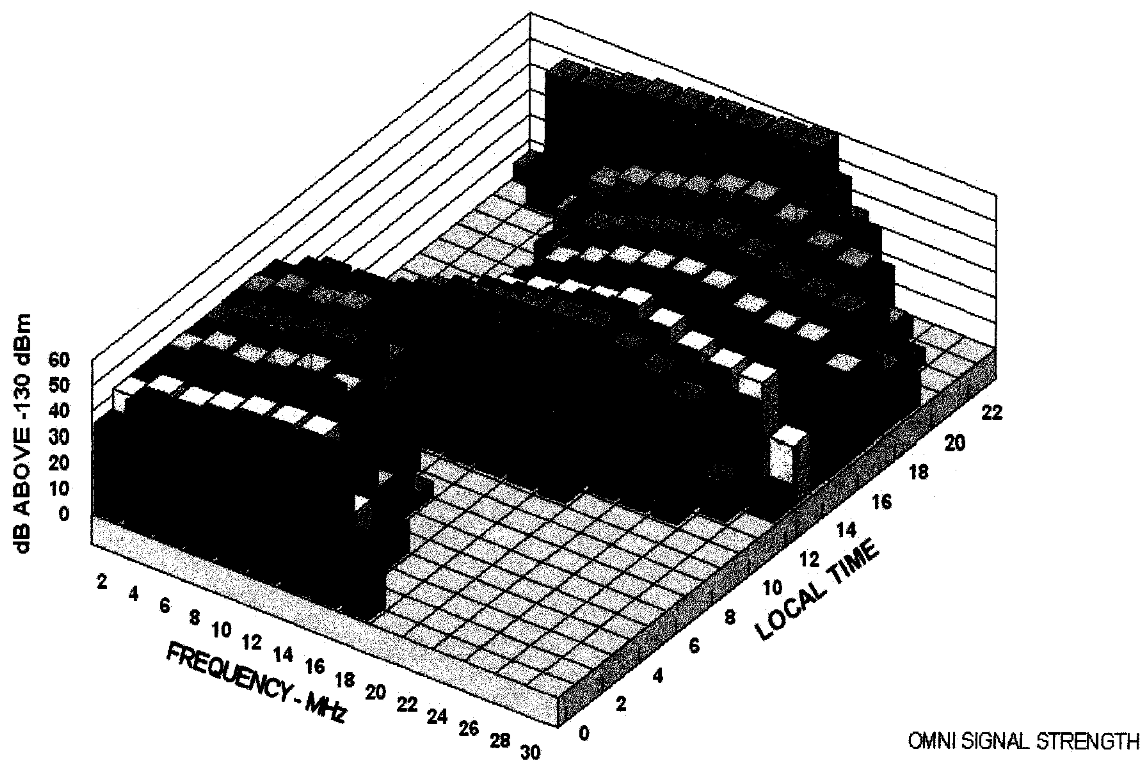

Figure 79 Signal Levels at the Antenna Output Terminals

The prior figure does not take into account the need for a margin in signal strength to detect and receive a signal at a low error rate. A signal-detection threshold of 12 dB was used for this example. In this example the detection margin was combined with the values of RFD loss and RFD noise to generate Output Plot 4 of the PET-2A program. These two items prevent the reception of some of the low-level signals. Figure 80 shows the remaining signals that can be detected by a receiver.

About 11% of the signals were lost due to the consideration of the detection threshold, RFD loss and RFD noise. This is a reasonable loss for these parameters at a practical site since there will be some signal loss between the antenna and a small amount of noise will be added by components in the signal distribution system.

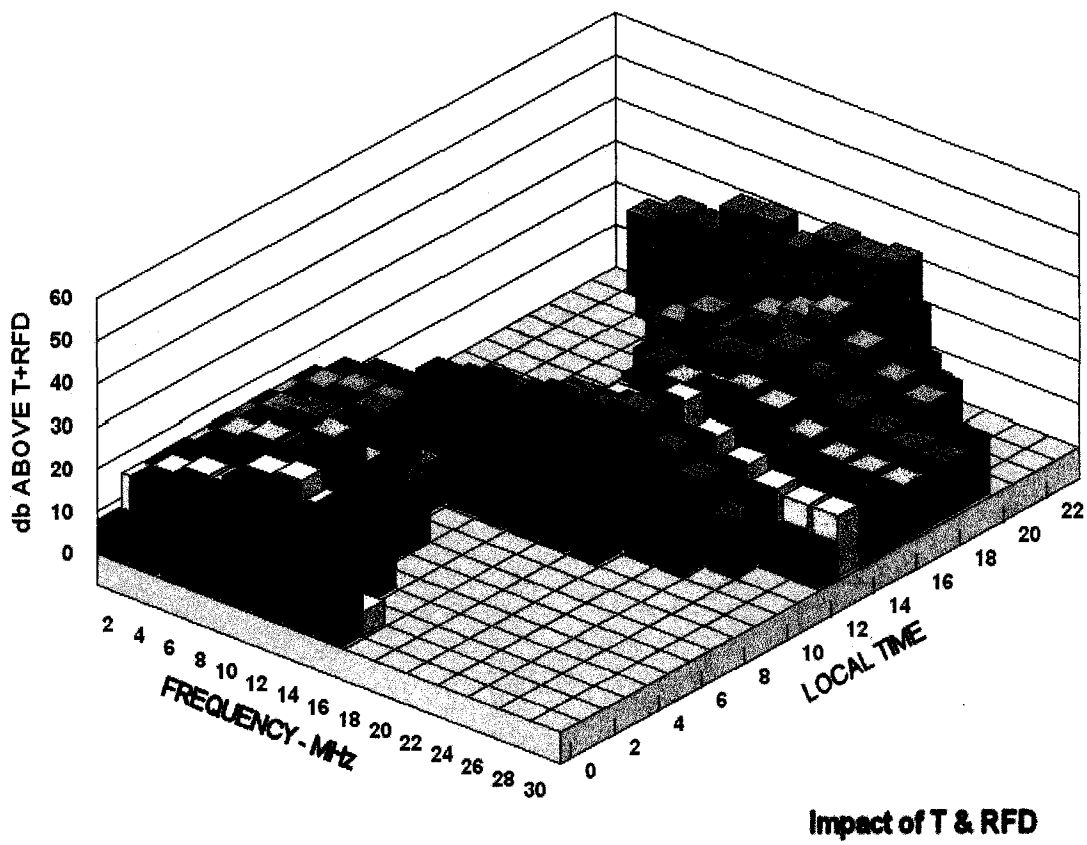

Figure 80 Signals Remaining after T+RFD

The high noise levels shown in the operating noise floor in Figure 79 suggest that additional signals will be lost when the man-made noise levels are considered. Figure 81 shows signals left when all site factors including the detection threshold, RFD loss, RFD noise, and man-made noise are considered. Man-made noise accounted for an additional loss of 46% of the signals impinging on the sites antennas from the selected source. This high loss indicates that considerable attention needs to be given to the mitigation of the sources of man-made radio noise if the site is to become an effective receiving site.

The PET-2A program can be repeated for additional signal sources and sources with different parameters as long as the sources are within the primary and secondary coverage areas of the receiving site. Such results provide a means to evaluate the present state of a site and to assess the effectiveness of noise-mitigation actions undertaken to improve signal reception.

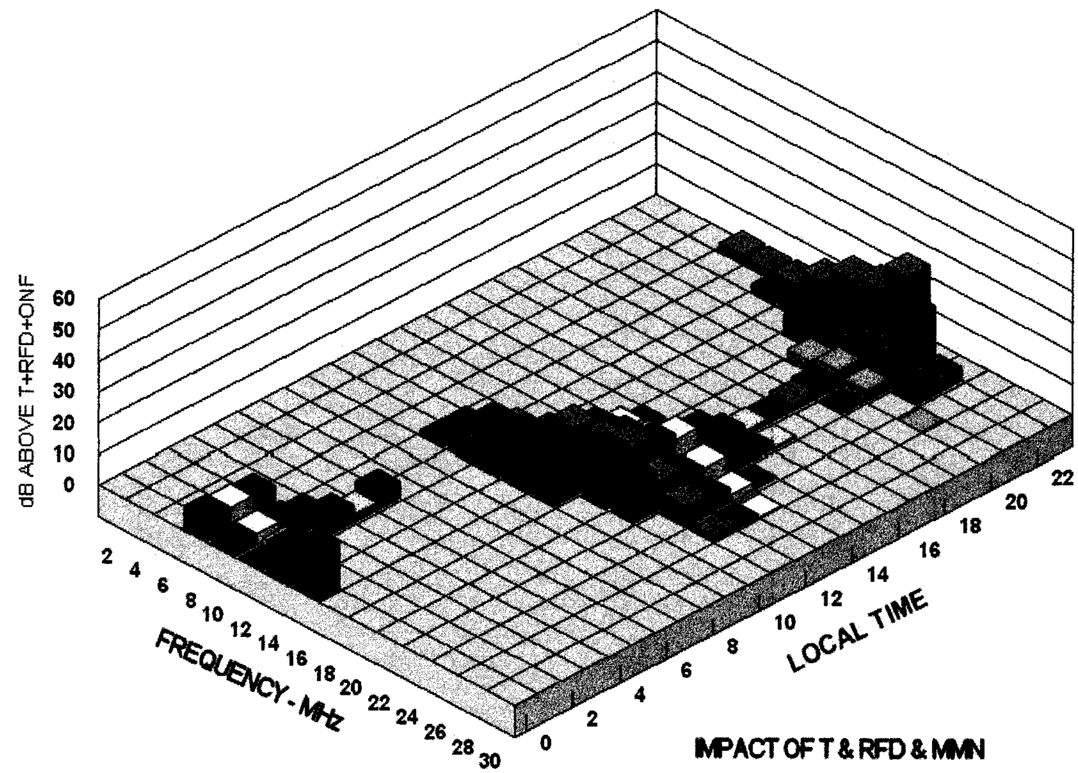

Figure 81 **Signals Remaining after T + RFD + MMN**

The above examples of the PET-2A program illustrate how a site manager can determine the ability of his site to receive radio signals. Additional outputs can be provided to further examine signal loss due to any component of a site.

A similar program is used to assess signal-reception loss at VHF and UHF sites.

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NAVAL POSTGRADUATE SCHOOL

THE MITIGATION OF RADIO NOISE AND INTERFERENCE FROM ON-SITE SOURCES at RADIO RECEIVING SITES

November 2009

by

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ABSTRACT *(maximum 200 words)*

Radio noise and interference from sources within the confines of radio-receiving sites is described and effective mitigation techniques are presented along with ineffective techniques. Of special concern is that many signals and most cases of noise and interference were non-stationary and could not be described with conventional stationary statistical techniques. Instrumentation used to cope with the intermittent and the time-varying properties of signals, noise, and interference is described.

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PREFACE

This document has been prepared for the designers, operators, and maintenance personnel of radio-receiving sites. Much of the information in this document also applies to data-processing facilities. The content is based on knowledge gained from extensive investigations of signal-reception issues conducted at more than 40 radio-receiving facilities as well as electromagnetic interference problems at a number of data-processing facilities. Much of the field work was conducted under the Signal-to-Noise Enhancement Program (SNEP) of the U.S. Naval Security Group (now disestablished). The SNEP program was about three decades in duration, a sufficient time to investigate signal-reception and signal-processing issues in depth.

This document was prepared because of the widespread lack of valid technical information about site performance at all levels of receiving-site operation. For example, the information about 'grounds and grounding' available to site personnel was especially confusing and often downright incorrect.

Complex analytical procedures have been avoided to make the text as readable as possible, but it is assumed the serious reader will have a good knowledge of the physical laws related to basic electricity. This includes an understanding of the flow of electricity in complex circuits, some understanding of the impact of reactive impedance on the flow of electricity, a basic knowledge of the properties of electric and magnetic fields surrounding conductors carrying electric current at both low and high frequencies, and the inductive and capacitive coupling of current and voltage from one conductor to another.

The basic principles of noise and interference mitigation techniques are also included. The integrated use of electromagnetic barriers, filters and grounds to confine electromagnetic noise to its source device is described. This is an effective technique to mitigate identified sources. Practical mitigation examples are described as well as ineffective solutions.

This is the first issue of this handbook. Time and funds for its preparation have been minimal thus some aspects have not been included. Additional editions will be required to keep it up to date and add additional pertinent material.

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LIST OF TABLES

1. INTRODUCTION

This handbook provides information about sources of radio noise and interference at radio-receiving sites where sources are located within the boundaries of a site. This includes sources that are within the main building, auxiliary buildings and other facilities associated with a radio-receiving site. Mitigation principles and techniques are included. A companion handbook[1] provides information about off-site sources of radio noise and interference and mitigation techniques for them.

The objectives of this handbook are simple. It is the provision of the information needed to design, construct, and operate a modern radio-receiving site that is free of harmful sources of on-site radio noise and interference, thus permitting a radio-receiving site to detect and process low-level radio signals.

In recent years on-site sources have become more pervasive due to the widespread use of power-conversion devices based on switching techniques. These devices convert electrical power from one form to another (e.g. direct current to alternating current, alternating current into direct current, a supply voltage to other desired voltages, the production of variable-frequency electric power, etc.) The widespread introduction of digital data-processing devices into radio-receiving sites has also resulted in many cases of increased noise levels at the input terminals of radio receivers. It is recognized that power-conversion and data-processing devices have added significant capabilities to radio-receiving sites, thus it is not the intent of this handbook to eliminate their use. It is the intent to provide the information needed to successfully employ such devices in and around a radio-receiving facility without degrading the ability of a site to receive low-level signals.

Extensive illustrations and examples of data are provided, along with photographs, to support the information and procedures contained in the handbook. Time-history views provide a means to examine the details of impulsive and time-changing noise, interference and signals. Broadband current probes are used to measure the properties of EMI current flowing on a variety of conductors in a site where the EMI (Electromagnetic Interference) current can consist of one or more discrete-frequency components, broadband noise and interference or commonly mixtures of both. The instrumentation used to provide examples of data for this document is described in Appendix A.

One additional complication is encountered while investigating signal-reception issues at radio receiving sites. Many signals are intermittent and occur at unknown times, at unknown frequencies, with unknown spectral and temporal properties and for unknown durations. Noise and interference is usually from multiple sources where each source produces noise and interference that is erratic in occurrence, erratic in temporal and spectral content and of erratic duration. In many cases the signals, noise and

[1] Wilbur R. Vincent, George F. Munsch, Richard W. Adler and Andrew A. Parker, ***The Mitigation of Radio Noise from External Sources at Radio Receiving Sites***, 6th edition. Report No. NPS-EC-07-002, Signal Enhancement Laboratory, Department of Electrical and Computer Engineering, Naval Postgraduate School, Monterey CA

interference fit non-stationary statistical rules rather than the conventional stationary statistical rules. Thus, simplistic measures of signals, noise and interference such as average, root-mean-square, peak, quasi-peak, amplitude probability distributions, etc. are not sufficient to even crudely describe many actual cases. To avoid the complexities of non-stationary statistical descriptions of signals, noise and interference in this document, graphical time-history views of signals, noise, and interference are provided. These views are calibrated in frequency, amplitude, and time duration as well as containing such information as date, time of day and location. Many of the views illustrate the difficulty of describing the properties of signals, noise and interference in simple terms.

The reader will find that some of the information in this handbook is considerably different from that in other sources, and in some cases it conflicts with the information from other sources. In such cases it is hoped the reader will rely on basic electrical theory to evaluate such differences and conflicts.

2. THE ON-SITE RADIO-NOISE PROBLEM

On-site sources of radio noise that adversely affect the reception of desired radio signals are a major problem, preventing the reception of low-level signals at many HF through UHF receiving sites. Figure 1 illustrates the general nature of the problem where the building housing the receiving equipment is shown as a rectangle outlined in black and with light yellow fill. A typical signal path from an antenna to a radio receiver is shown in blue. Noise sources are shown in red ovals, and typical entry paths from sources into the RF path are shown as red dotted lines.

Many sites have outlying facilities which also contain sources of noise. These are shown by the red oval titled "Nearby Sources," and noise from such sources can be received by the site's antenna and be passed along to the input terminals of a receiver. Other sources can be inside the receiver building where it can leak into the RF paths by a variety of mechanisms. Still other sources of radio noise can be generated by filters, switches, amplifiers, and other components within the RF distribution system which are saturated thus generating intermodulation products and intermodulation noise.

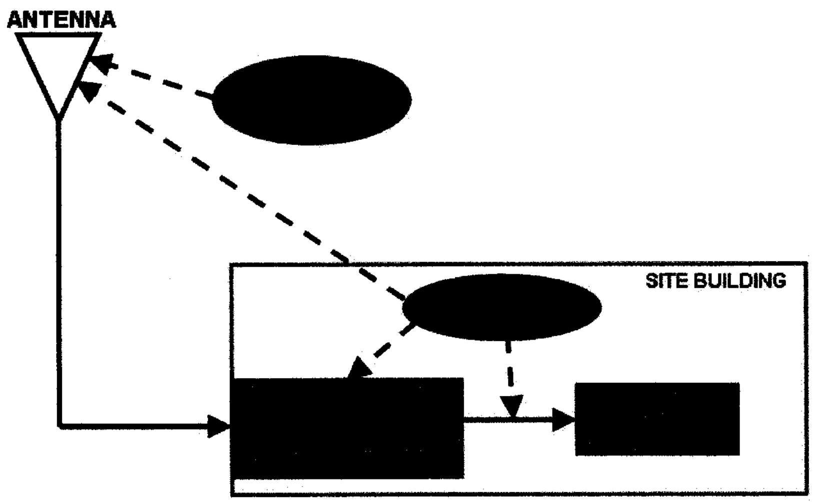

Figure 1 Block Diagram of On-Site Sources

Each item in the block diagram of Figure 1 will be dealt with in subsequent parts of this document. Emphasis is given to identifying sources, understanding the paths radio noise takes from its source to the input terminals of a receiver, and the application of effective mitigation actions. Numerous examples will be provided to support the implications presented in the block diagram.

Of special interest is that all of the sources and the associated paths radio noise takes to appear at the input terminals of a radio receiver are completely within the control of site planners, site managers, and site operators. Eliminate the sources and/or the paths of entry of the noise into the RFD, and radio noise and interference problems will disappear.

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3. RECEIVED SIGNALS

3.1 Signal Dynamic Range

Some information about the nature of ambient signals delivered by an antenna to the RF-distribution system of a site and its receivers is necessary to fully understand the adverse impact of radio noise and interference on the reception of signals. Thus a brief description of some aspects of received signals is provided for background information.

Figure 2 shows the amplitude of signals received at an HF site from a vertical monopole antenna over the frequency range of 7.7 to 17.7 MHz. The signals in this example were received at 1600 hours local time, a time-of-day of minimum signal amplitudes. Signals above and below the frequency range were very low in amplitude due to radio-propagation limitations and were excluded from the data. The clusters of high-level signals originate from transmitters in the International Broadcast Service. The common wavelength identifiers of each international broadcast band are shown above each cluster. Signals in between the clusters of high-level signals are from other radio services and are normally the signals of highest interest to a receiving site.

At nighttime when ionospheric absorption is low, HF signals will be 30- to 50-dB higher in amplitude than shown in Figure 2.

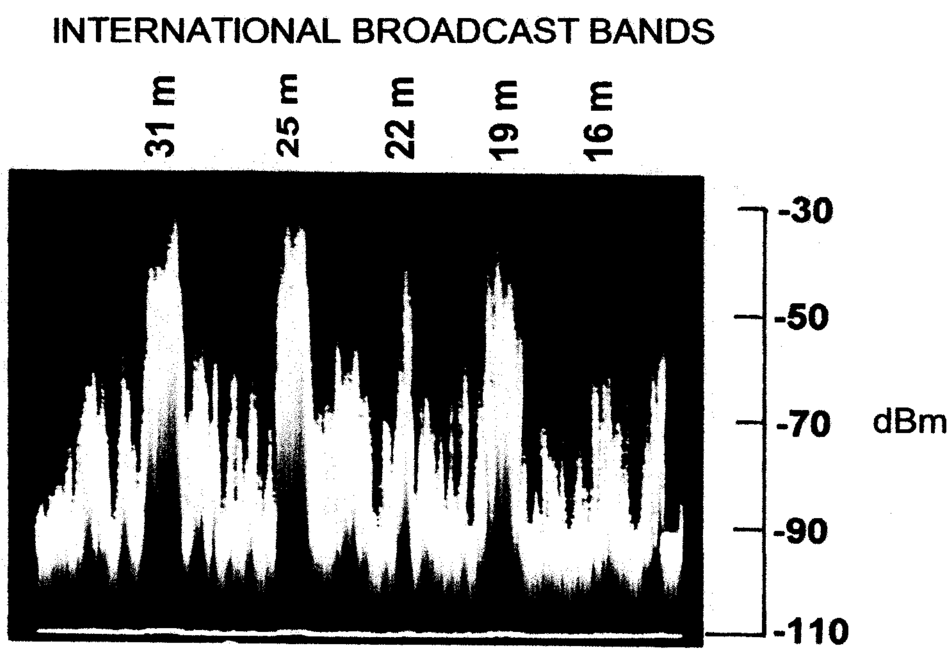

Figure 2 Example of Daytime Signal Levels in the HF Band

Similar signals levels can be found at other HF receiving-sites since the distribution of transmitting sources is widely spread around the earth. Only minor site-to-site variations have been noted during measurements at more than 40 radio-receiving sites.[2]

The total ambient signal power at the output terminals of an HF antenna was measured at 2-hour intervals over four days at a European site, and Figure 3 shows the result where a band-pass filter was used to exclude out-of-band signals. This example shows the broadband signal power within the 2- to 30-MHz frequency range that was delivered to the site's RF-distribution system and on to the input terminals of the site's radio receivers. All broadband devices in the site's RF-distribution system and the receivers must have sufficient dynamic range to handle the total signal power while still receiving low-level signals.

Most HF and VHF/UHF receivers are capable of detecting a signal as low as -130 dBm in a 3-kHz bandwidth. This indicates that a broadband dynamic range of about 100 dB is required for all components in the RF distribution path during the daytime and up to about 140 dB at the nighttime hours. Any linear component in the RF-distribution system and in the broadband portion of a receiver that does not have this dynamic range will saturate and cause excessive intermodulation products and intermodulation noise which will appear at the input terminals of the receiver. Since the needed dynamic range is extremely difficult to achieve in standard broadband amplifiers and in receivers, automatic gain control is often used to limit the operating range of amplifiers and receivers at the expense of losing low-level signals.

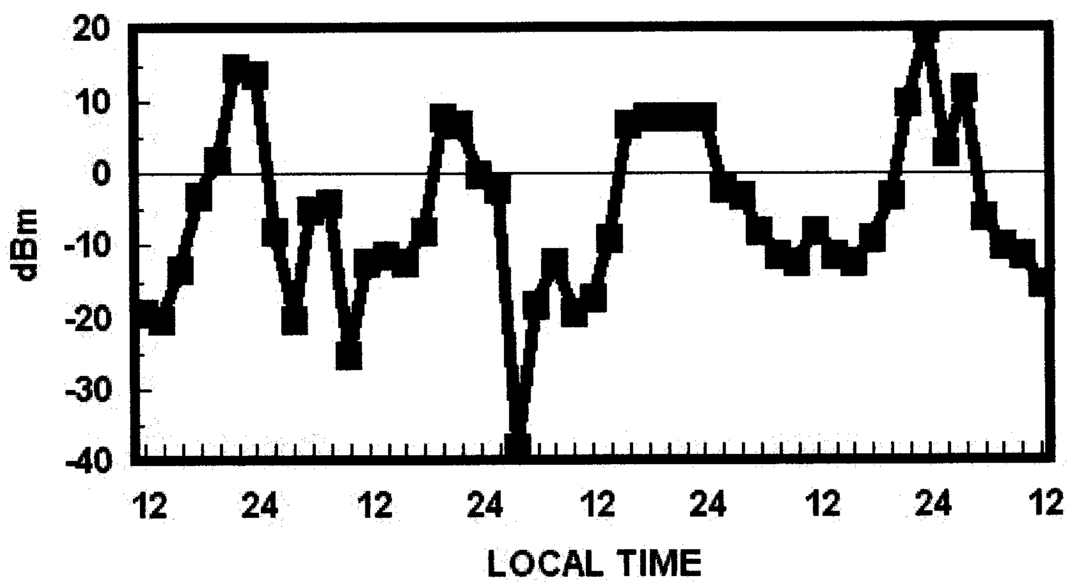

Figure 3 **Diurnal Variations in Total HF Received Signal Power**

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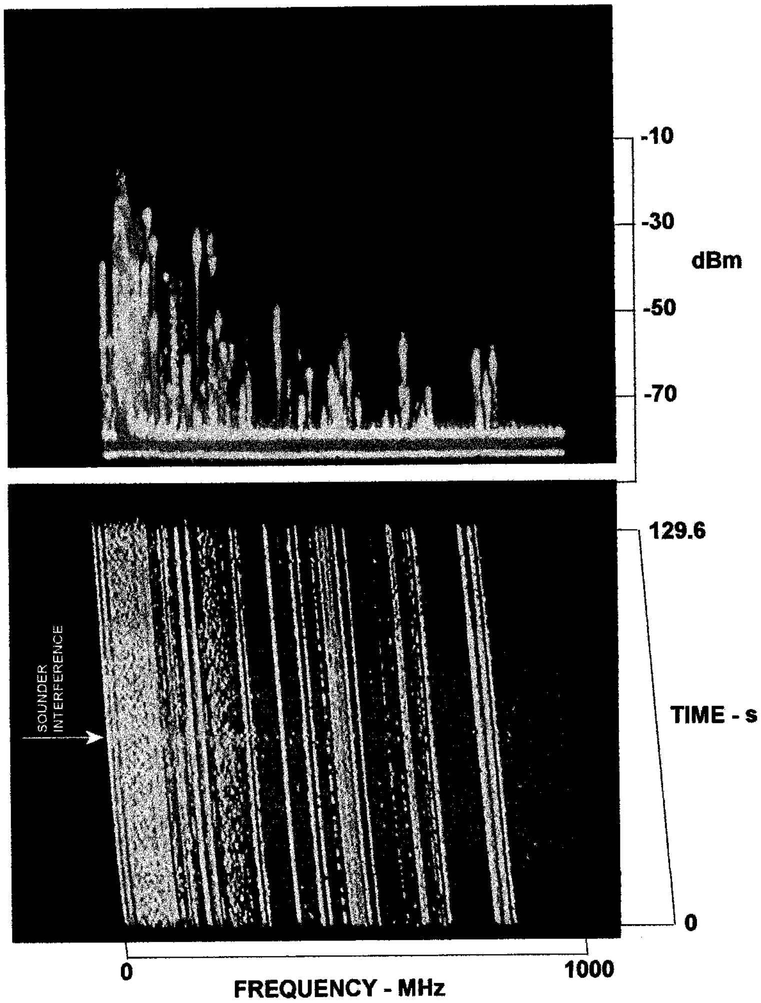
2 Wilbur R. Vincent, Richard W. Adler and George F. Munsch, ***An Examination of Man-Made Radio Noise at 37 HF Receiving Sites,*** Report No. NPS-EC-05-003, Signal Enhancement Laboratory, Department of Electrical and Computer Engineering, Naval Postgraduate School, Monterey, CA

Figure 4 shows a typical example of signal levels in the VHF band. In this case the primary strong sources are FM and Television stations located on nearby hill or mountain tops that are within line of sight. Occasionally one will encounter strong signals from other nearby sources such as mobile or fixed communications sites.



K-VHF, 28A/29A, 080923, 1421, 500, 1000, 30, 1000, A1-V, NF, 0, 0, -10
SOUNDER AT 15 WATTS

Figure 4 Example of Strong Signals in the VHF Band

Experience has shown that the RF Distribution System at many sites contains components that lack sufficient dynamic range for effective signal reception. This is especially the case for nighttime signal reception at HF sites and at VHF/UHF sites that have nearby transmitting facilities. Site designers, managers, maintenance personnel and operators must take into consideration the presence of high-level signals from nearby sources and their potential impact on the reception of desired low-level signals. All components in the signal path from an antenna to a receiver must have sufficient dynamic range to cope with the total signal power delivered by the antenna.

4. FACILITY GROUNDS

4.1 General Comments

Grounds are often misunderstood, misused, mistaken, and confused by site designers and site operators. Added to the confusion are the numerous names that are used for grounds. A partial list of these names includes:

Single-point ground
Multiple-point ground
Signal ground
Red ground
Black ground
Green-wire ground
Shield ground
Radio-frequency ground
Computer ground
Equipotential ground
Room ground
Facility ground
Power ground
Electrical ground
Earth ground
Lightning ground
Antenna ground

With the proliferation of names, many of them without a precise technical definition, it is no wonder that grounds are a confusing topic to the designers, managers, and operators of a receiving site.

An additional vital, but often ignored, aspect of all ground conductors in a site is that they can, and do, conduct unwanted levels of EMI current and voltage from their source(s) to other locations in a site. This is further complicated by the electrical connection of a site's ground conductors to many other conductors such as equipment cases, equipment racks, electrical fixtures, communications cable shields, coaxial cable shields, conduits, and even the building structure. All such conductors are a part of the total electrical and RF ground system of a site, and no part of this total ground system can be ignored when investigating electromagnetic interference problems.

The following discussion will attempt to eliminate some of the confusion about site grounds.

4.2 The NEC® Ground

The National Fire Protection Association (NFPA) publishes the National Electric Code® (NEC®). The NEC specifies details of a comprehensive ground system for all buildings with electric power. The NEC ensures that facility and personnel safety is maximized, and all sites operated by US entities should be in full compliance with the NEC. The NEC describes an earth ground located at the entrance of electric power into a facility, and it specifies the use of green-wire-ground conductors for the supply of electric power to all devices within a facility that use electric power.

The sole purpose of the NEC green-wire ground is for the safety of equipment and personnel. No additional ground system or set of ground conductors is needed to satisfy the equipment and personnel safety requirement of the NEC at a receiving site or at any other facility.

Each site should have a copy of the most recent edition of the NEC[3] and have someone fully trained in the use of, and full compliance with, the NEC. Of interest is that several individuals and organizations offer excellent training for the NEC[4].

4.3 An Additional Aspect of the NEC Green-Wire Ground

The NEC green-wire ground conductors, as well as their associated electric-power conductors and metal conduits, often carry harmful levels of current and voltage throughout a site at frequencies higher than the electric power-related frequencies considered by the NEC. The NEC green-wire conductors as well as additional conductors such as cable shields, conduits, cabinet surfaces, equipment racks, and even the building structure also carry unwanted levels of EMI current from sources to victims. The high-frequency aspects of the flow of electric current and voltage in grounds is not covered by the NEC, and an understanding of the adverse impact of such current and voltage on the reception of radio signals is essential as well as the mitigation actions needed to reduce such current and voltage to harmless levels.

Knowledge of the basic rules for the flow of electricity is essential in understanding the full role of ground systems. Two factors must be considered. The first is that low-frequency EMI current flows in complete circular paths from its source back to its source. This circular path may be simple, or it may be complex due to connections to other conductors. The exception to this simple circular rule is that current and voltage can be coupled by magnetic fields that surround all current-carrying conductors (inductive coupling) and by electric fields from voltage on conductors (capacitive coupling) onto all other nearby conductors. This provides even more paths for high-frequency current and voltage to reach the input terminals of a receiver. This is highly important because of the very close proximity of conductors carrying EMI current and voltage to many other conductors and conducting objects in a receiving site.

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3 Copies of the National Electric Code (NEC 2008) can be obtained from NFPA Headquarters, 1 Battery Park, Quincy MA, 02169-7471, any of its regional offices, or from many commercial organizations. Further information is available at www.nfpa.org

4 One excellent source of training in the NEC is www.mikeholt.com

In addition, the flow of high-frequency EMI current on the electrically-long conductors commonly found in a receiving site will result in current and voltage peaks and nulls with distance along a conductor These peaks and nulls are identical to the standing waves found on unmatched transmission lines and on antennas. Thus, the magnitude of high-frequency current and voltage along a ground or along a conductor of any kind will change significantly with distance and with frequency.

In this handbook, the measurement and documentation of EMI current from the magnetic fields that surround a conductor is emphasized rather than EMI voltage from the electric fields between the conductors. This is because a definitive value of EMI current can be obtained at any selected measurement point along a conductor with an appropriate current probe placed around a conductor. However, the measurement of EMI voltage requires a zero-voltage reference point which is virtually impossible to obtain in a receiving site except at the exact source of an EMI current or voltage. Since multiple EMI sources are common in a facility, a zero-voltage reference is almost impossible to obtain at the high frequencies of concern because of standing waves. A ground bus or system, no matter how large or extensive, cannot provide a zero-voltage ground reference at the high frequencies encountered at receiving sites.

One additional complication needs consideration. Most EMI voltage and current flowing on conductors in a receiving site is highly impulsive, thus contains frequency components over a very wide part of the radio spectrum. Because of this, wide-band measurement techniques are essential to measure, document and understand EMI flowing on ground conductors, or any other conductor, as well as discrete-frequency measurements. Also of interest is that a description of the spectral and temporal properties of EMI current and/or voltage is often highly useful in identifying sources.

To further complicate the understanding of a ground is that high-frequency EMI current and voltage flowing on grounds and other conductors often changes in value with time. This includes the occurrence of transients as well as sudden and large changes in current and/or voltage as sources are turned on and off. Thus, knowledge of the time history of changes of current and voltage is essential in diagnosing intermittent problems associated with erratic EMI current flowing in grounds.

Figure 5 shows an example of standing waves along ground conductors for two equipment racks and along the conduit providing power to the racks. EMI current was injected into a ground bus at the power panel supplying power to equipment in the racks. Current was injected at a series of fixed frequencies and at a level of 750 μA rms. The injection level was set to the ambient broadband EMI current level flowing on the ground bus at a frequency of 2 MHz at this receiving site. The blue curve shows the measured current flowing in a ground bus at an equipment rack located about 10 feet from the injection point and as the injection frequency was varied. Peaks and nulls were found with frequency similar to the peaks and nulls found on a transmission line or an electrically long antenna. At the high-frequency end of the data, current peaks on the ground bus significantly exceeded the injection level.

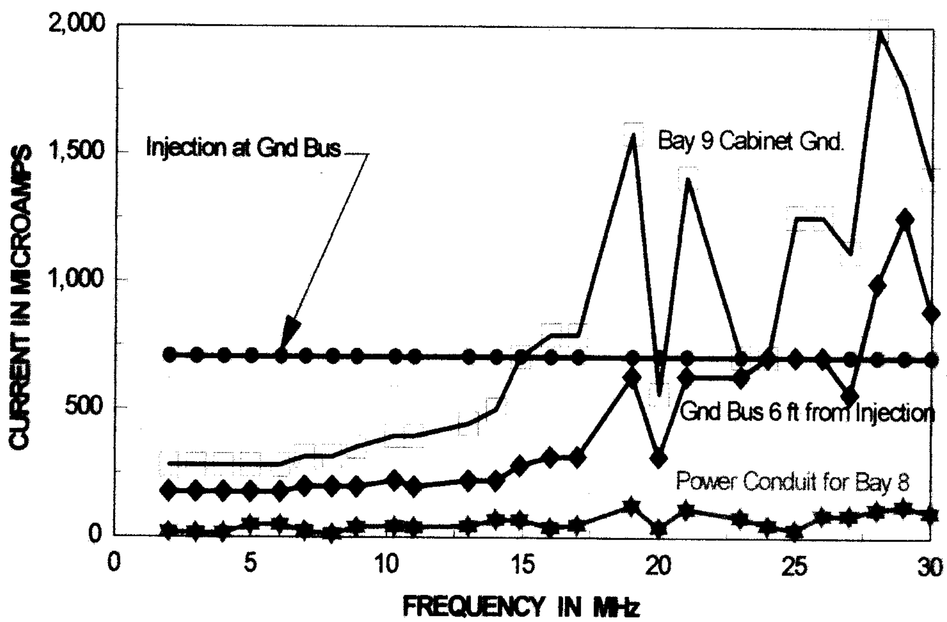

Figure 5 **Standing waves along Ground Conductors**

EMI current was also measured on a second ground bus leading to another nearby equipment rack as shown by the red line on the graph. Similar standing waves existed on this ground bus although at a lower level. EMI current was also measured on a power conduit as shown by the green line. It was somewhat more orderly and exhibited only minor variations with frequency. In this case the conduit was located on a cement floor and was separated from the ground busses and the ground busses were isolated a few inches above the floor. The conduit also fed electric power to another set of equipment racks, thus it did not provide a good closed path from the source of the EMI current back to its source.

The data in Figure 5 show that grounds are not simple devices where the flow of current and its associated voltages are described by the limited concepts of direct current and voltage or at the low frequencies of the electric power system. The reactive impedance aspects of electrically-long grounds and conductors carrying EMI current must be considered in modern sites. The data show that zero-voltage points simply do not exist at any point along the ground system except at the exact point of injection of EMI current into a ground conductor. Additional information about the broadband nature of EMI current will be presented later in this document.

Other electrically-long conductors can carry high-frequency EMI current such as cable shields and common-mode current flowing in unshielded cables, and they also will have standing waves for discrete-frequency cases. Standing waves were explored further using a multi-conductor cable 250 feet in length (Cable 1) placed on the ground in an open area. A second cable (Cable 2) was placed adjacent to and parallel with the first one. A constant level of current was injected into the shield of Cable 1 at a frequency of 2 MHz, and the shield current was measured at 10-foot intervals along the cable. The dark line on the plot of Figure 6 shows the current magnitude along the length of Cable 1. The distinctive standing waves on the cable shield are identical to those along a long-wire antenna.

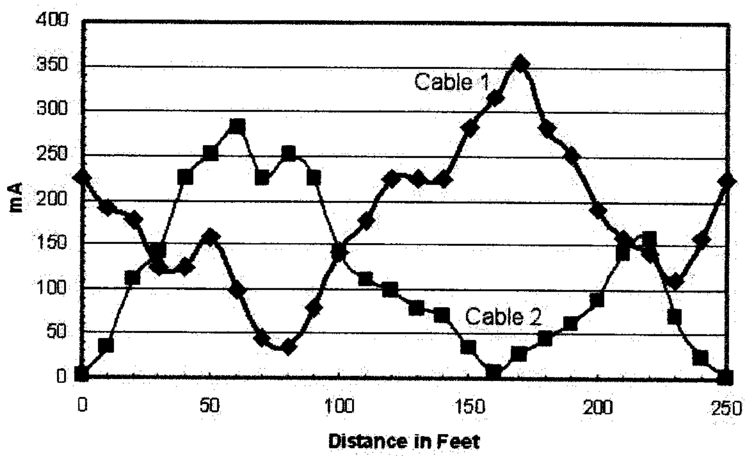

Figure 6 Variation of EMI Current Level on Cable Shields with Distance

Next, one must consider the very tight coupling of EMI current and voltage from one conductor to another nearby conductor. The mutual impedance from one conductor to another nearby conductor (especially conductors in the same cable bundle) is very low, thus high-frequency current and voltage is efficiently transferred from one cable to another by inductive and capacitive field coupling. This is shown by the lighter line in Figure 6. Note that the current in Cable 2 also varies with distance, but it is opposite in phase. The current is near zero at each end of the second cable and peaks at approximately the nulls of the current in Cable 1. The data is not entirely smooth since the ground material under the cables was not uniform along the cable length and the cables were not perfectly straight nor evenly spaced apart over their length.

The example shows that the tight coupling of EMI current and voltage from one conductor to another nearby conductor greatly enhances and complicates the spread of EMI current and voltage throughout a site. A single conductor with excessive levels of EMI current or voltage can efficiently infect other conductors and provide paths for EMI current and/or voltage to enter leakage points in signal paths.

The two examples show the distinctive standing waves formed by a discrete-frequency source of EMI current. In actual cases, the EMI current often contains broad-band spectral components rather than a single spectral component as was used to obtain the standing-wave plots. Thus, overlapping standing waves will exist and the peaks and nulls of the standing wave current will be smoothed into a more continuous shape.

4.4 Other Ground Systems

Receiving sites sometimes contain other ground conductors and ground systems in addition to the NEC Green-wire ground. In addition, many other conductors such as cable shields, conduits, equipment-rack and cabinets, and the metallic parts of the building structure are all electrically connected to the NEC green-wire ground. It is common practice to bond together large used and unused metallic objects such as equipment racks and cabinets from a general electrical safety standpoint. All of these conductors are a part of a site's ground system.

The shields of antenna and communications cable should always be grounded to earth at their entrance point into a building with a suitable termination plate and a short conductor bonded to an earth ground rod as specified by the NEC.

Equipotential ground systems are sometimes added to a receiving site, or a portion of a site, where the stated reason is usually to provide a near-zero-voltage reference for electronic systems and components. Unfortunately they only provide a near-zero voltage reference and an equipotential surface when their dimensions are electrically less than about 1/20th of the wavelength of the highest-frequency EMI current that flows in such a ground system. Since the wavelength of EMI current flowing in the grounds of modern sites is physically much shorter than the dimensions of any practical equipotential ground systems, standing waves of current and voltage will exist across its surface similar to that shown in Figure 4 for a linear ground conductor and similar to that found on a flat-plate antenna operating at frequencies where the signal's wavelength is shorter than the antenna dimensions. Thus equipotential ground systems cannot provide an equipotential surface or reference in a modern site, and they are not effective in controlling EMI problems. In many cases an equipotential ground will exacerbate EMI problems in a site rather than correct or minimize such problems because they effectively inductively and capacitively couple EMI current (magnetic fields) and voltage (electric fields) to many nearby conductors.

In past years the equipotential ground was effective when one needed to provide an equipotential surface only at the fundamental and the low-order harmonics of the electric power frequency. This changed with the introduction of modern digital devices and power-control systems into receiving sites along with the accompanying high-frequency and broadband spectral components of EMI current and voltage.

The use of a so-called equipotential ground system in a receiving site is no longer practical, and their use can be detrimental to site performance.

Some sites contain additional ground systems. In all cases a valid technical reason should be clearly stated for additional ground conductors and systems other than the NEC green-wire system.

4.5 Earth Ground

Some documents state, or imply, that grounding a device or system that contains a source of high-frequency EMI current and/or voltage to earth (or equipment that is susceptible to EMI) will correct EMI problems. Furthermore some documents state that the earth actually absorbs EMI. These statements are highly misleading and are often downright incorrect. They are not supported by the accepted principles of basic electricity.

A review of Ohm's law[5] and Kirchoff's[6] first law of current flow and his second law of voltage is useful in understanding the flow of low-frequency EMI current in a complex multi-path ground circuit. The concepts developed by these two individuals have withstood several centuries of tests and experiments, and they describe the flow of low-frequency EMI current and its associated voltages in electrical circuits including ground conductors. Only minor modifications to their laws (with the introduction of circuit impedance in addition to resistance) are needed to describe the flow of EMI current in ground systems at higher frequencies as well as the presence of standing waves of current and voltage (hence magnetic and electric fields) on ground conductors.

The electrical path into an earth ground rod is always considerably higher in resistance and in reactive impedance than other paths within the complex configuration of ground conductors and other metallic conductors of a site. Since EMI current will always flow in the path of lowest impedance, it will flow primarily in the other metallic paths, and only insignificant levels of EMI current will flow into the higher impedance path of a ground rod and into the earth. Numerous attempts to measure EMI current flowing into the ground rods at a number of receiving and data-processing sites have shown such current to be insignificant and orders of magnitude lower than the EMI current flowing in other conductors of these sites.

While an earth ground is absolutely necessary to comply with the personnel and site-safety requirements of the NEC, it does not provide a useful means to control or eliminate high-frequency EMI in a receiving site. Furthermore, there is no valid physical or electrical mechanism associated with an earth ground that will permit the absorption of alternating EMI current or voltage into the earth; however the earth and an earth ground do play a significant role in the control of static discharges from lightning and for the safety requirements of the NEC.

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[5] Georg Simon Ohm formulated his law of current flow in a resistor and the voltage drop across a resistor while a high-school teacher and published his findings in 1827.

[6] Gustave Robert Kirchhoff formulated his two electrical circuit laws in 1845 while a university student in Germany. These two laws remain the fundamental means of determining the performance of circuits at direct current and at low alternating current frequencies in circuits were impedance is low.

4.4 Antenna Related Grounds

It is beyond the scope of this document to provide detailed information about ground systems for antennas, and there are numerous references available to antenna designers on the topic. However, most forms of monopole receiving antennas require a ground counterpoise or mesh to provide a path for the flow of image current. This is commonly provided by the counterpoise wires or a ground mesh located under and around a monopole antenna. Such wires provide a lower-impedance path for the flow of image current than an earth-ground path. Counterpoise wires should never be used for any other purpose such as a general electrical or lightning protection ground system.

Since ground counterpoise conductors are an integrated part of the antenna system, and all other nearby conductors must be free of EMI current to avoid coupling harmful levels of such current into the counterpoise conductors. This includes power and communication cables that are buried below the counterpoise conductors or supported above them.

4.5 Other Factors

Always use standard compression fittings and/or stainless-steel bolts to connect sections of a ground system together. Firmly tighten all joints.

Never use welded or CADWELD® joints in a ground system or at any other location in a receiving site. Numerous cases of poor welding have been noted in receiving sites which can be blown apart with a sudden surge of fault current. In addition, contamination in welded joints can result in inclusions with non linear electrical properties. These can produce intermodulation components and intermodulation noise when EMI current flows through them.

5. TYPICAL SOURCES OF NOISE AND INTERFERENCE

5.1 General Comments

A variety of sources have been identified that inject harmful levels of radio noise and interference into the RF paths leading to radio receivers, and a number of typical examples are described in this section along with examples of the problems generated.

5.2 Saturated Components in the RF Paths

The saturation or overload of components in RF paths between an antenna and a receiver from the normal ambient signal environment and from high levels of man-made interference is a common source of unwanted and harmful radio interference. Examples of such components are broadband amplifiers, multicouplers, signal dividers, RF filters, and dirty and/or corroded coaxial connectors. Welds on galvanized steel used on antenna towers, antenna components, ground conductors, antenna supports, and objects near an antenna also have nonlinear characteristics that will saturate at very low levels of RF current. These kinds of sources produce unwanted radio interference from intermodulation (IM) components and broadband IM noise.

Figure 7 shows a brief burst of intermodulation noise caused by a strong signal burst that overloaded the amplifier of a multicoupler. Such bursts of IM noise can be similar to some short-duration signals, and when present they put an unwanted burden on a receiving system which must differentiate them from desired signals.

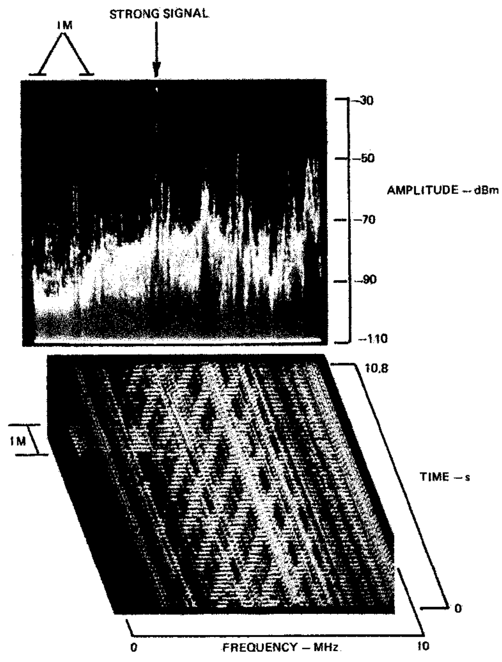
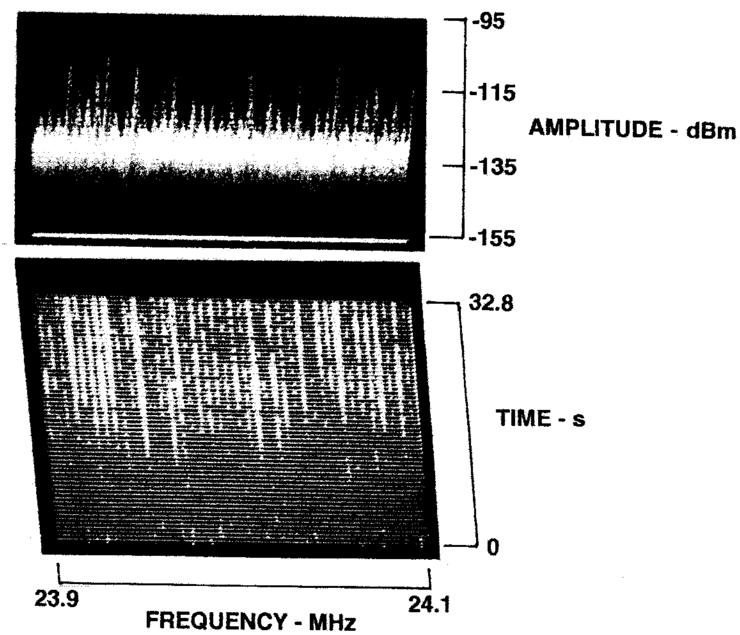


Figure 7 In-Band IM Noise

Figure 8 shows another example of interference caused by saturated components in an RF path to a receiver. Multiple high-level signals from international broadcast stations in the HF band exceeded the dynamic range of a component in the RF path and caused the closely-spaced IM products. In this case the broadcast signals were all below the frequency range shown. Ionospheric propagation limitations prevented normal signals from being received within the frequency range of the example at the time of day of the example, thus all of the spectral components in the view are IM products. The reduction in amplitude of the IM products in the lower one-third of the time-history view is because of fading of the ambient signals that overloaded the RF components. The maximum amplitude of the IM products is shown in the upper amplitude-vs.-frequency view. Additional IM products also existed at lower and higher frequencies, including the lower frequencies where the broadcast signals were received.



HAN, PASTEUP, 930930, 0130, 24, 0.2, 1, 500, A30, BPF (2-30), 38, -10, -20

Figure 8 Above-Band IM Products

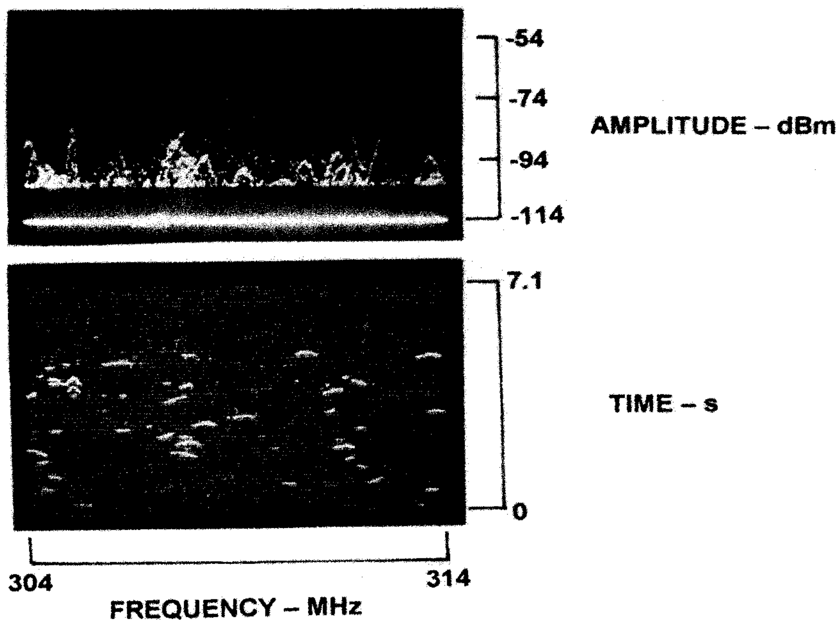
The term IM product refers to the textbook description of intermodulation where two or more discrete-frequency signals applied to a nonlinear component produce harmonics of each signal and other products in accordance with the following:

$$f_{IM} = mf_1 \pm nf_2 \pm of_3 \ldots\ldots\ldots$$

where f_{IM} is the frequency of each intermodulation product generated.
$f_1, f_2, f_3 \ldots\ldots$ are discrete-frequency signals applied to a nonlinear joint.
$m, n, o \ldots\ldots$ are integers from 1 to a higher number.

The term "IM noise" is also used throughout this document. Since f_1, f_2, f_3... are often not pure discrete frequencies but are normal signals that have spectral width, the IM products will also have spectral widths but with widths multiplied by m, n, and o...... When the spectral widths of the ambient signals are wide as in many practical instances, the IM products will appear as broadband noise. Thus, both terms IM products and IM noise describe two important aspects of intermodulation.

The previous Figure 7 shows one example where a strong signal about one-second in duration produced IM products and noise also about one-second in duration. Even shorter duration IM products and noise can occur, and Figure 9 shows an example. In this case a frequency-hopping transmitter emitting pulses in the low portion of the VHF band was operated adjacent to a receiving facility. Its strong VHF signals overloaded components in the RF path and produced high-level impulses of IM noise from 60 MHz up to 1000 MHz. Figure 9 shows an example of the resulting IM pulses in a 10-MHz wide portion of the radio spectrum centered at 309 MHz.



BAT, PASTEUP, 990812, 0735V, 309, 10, 300, 100, F(287.5), 24, 0, -10

Figure 9 Intermodulation Pulses in the UHF band from a VHF Source

Two factors contributed to the excessive IM products and noise shown in Figure 9. First, the VHF frequency-hopping transmitter was operated too close to the receiving antenna thus resulting in extremely high electromagnetic-field levels at the receiving antenna. Second, a very low-dynamic-range multicoupler was incorporated in the RF path between the receiving antenna and the receiver, and it could not handle the normal signal environment.

5.3 Cable Leakage

Leakage of noise and other spectral components into RF cables running from antennas to receivers has been noted at all receiving sites that use single-shielded coaxial cables. Receiving sites using high-quality double-shielded coaxial cable and properly-assembled coaxial connectors seldom encounter cable-leakage problems.

Figure 10 shows an example of severe leakage encountered at a receiving site. In this case a 5-MHz frequency-reference signal was distributed throughout the site over single-shielded RG-58 coaxial cable[7]. Radio signals were carried from the entry into the building and to receivers on single-shielded cables. Leakage of the reference signal and a second lower-level signal into a single-shielded cable feeding the receiver was exceptionally high. Of interest was that no detectable leakage was found in a parallel double-shielded coaxial cable feeding another receiver. This example clearly indicates that the use of single-shielded coaxial cable in a receiving site must be prohibited.

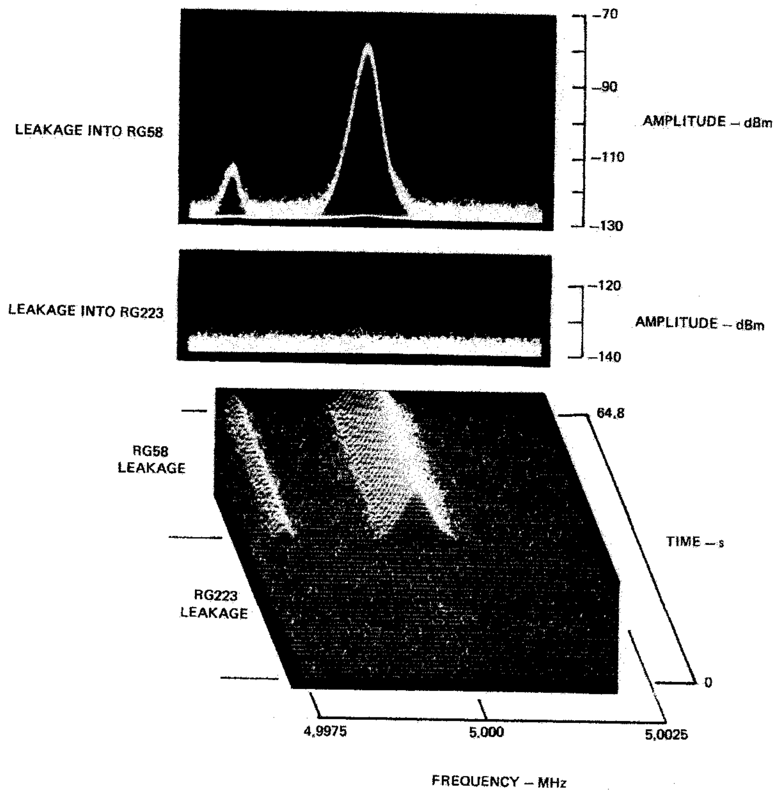


Figure 10 Example of Leakage into Coaxial Cables

To better understand the leakage of signals from one cable to another, two single-shielded cables (type RG-58) fifty feet long were run in a straight line along the earth. Two fifty-foot double-shielded cables (type RG-223) were added to the configuration.

[7] See Section 8 for a discussion of coaxial cable designations, old and new.

Test signals were first injected into one of the single-shielded cables and then into one of the double-shielded cables. The far end of each driven cable was terminated in a fifty-Ohm coaxial terminator. The far ends of the un-driven cables were also terminated with 50-Ohm terminators, and the signal levels that leaked into the un-driven cables were measured with a spectrum analyzer at frequency intervals from 5 to 25 MHz.

Figure 11 shows the result of this measurement where the leakage loss is expressed in dB. The single-shielded to single-shielded coaxial cable provided only about 70 dB of isolation near the center of the frequency range while the double-shielded to double-shielded loss was greater than 140 dB (not measurable with the test setup available). The single-shielded cable to single-shielded isolation is clearly insufficient to provide acceptable signal isolation from one antenna cable to another since at least 130 dB of cable-to-cable isolation is needed to the avoid cross talk of received RF signals. The isolation provided by single-shielded to double-shielded cable also did not meet the needed isolation levels. Because of these findings only double-shielded coaxial cable should be used throughout a receiving site.

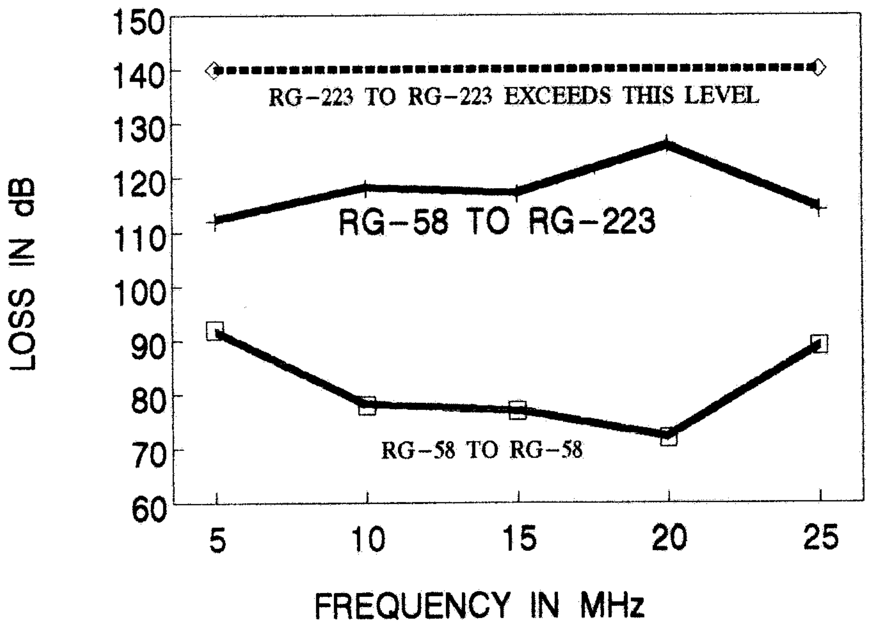


Figure 11 Cable-to-Cable Coupling Loss

The upper view of Figure 12 shows signals and noise at the input terminals of a receiver when an improperly assembled coaxial connector was installed on a coaxial cable in the RF-Distribution path for that receiver. The shield of the cable was open at one end enabling EMI current and voltage on the cable shield to enter the signal path. The noise floor over the low-frequency portion of the frequency range is excessively high. The lower view shows the reduction in the noise floor when the shield was properly connected.

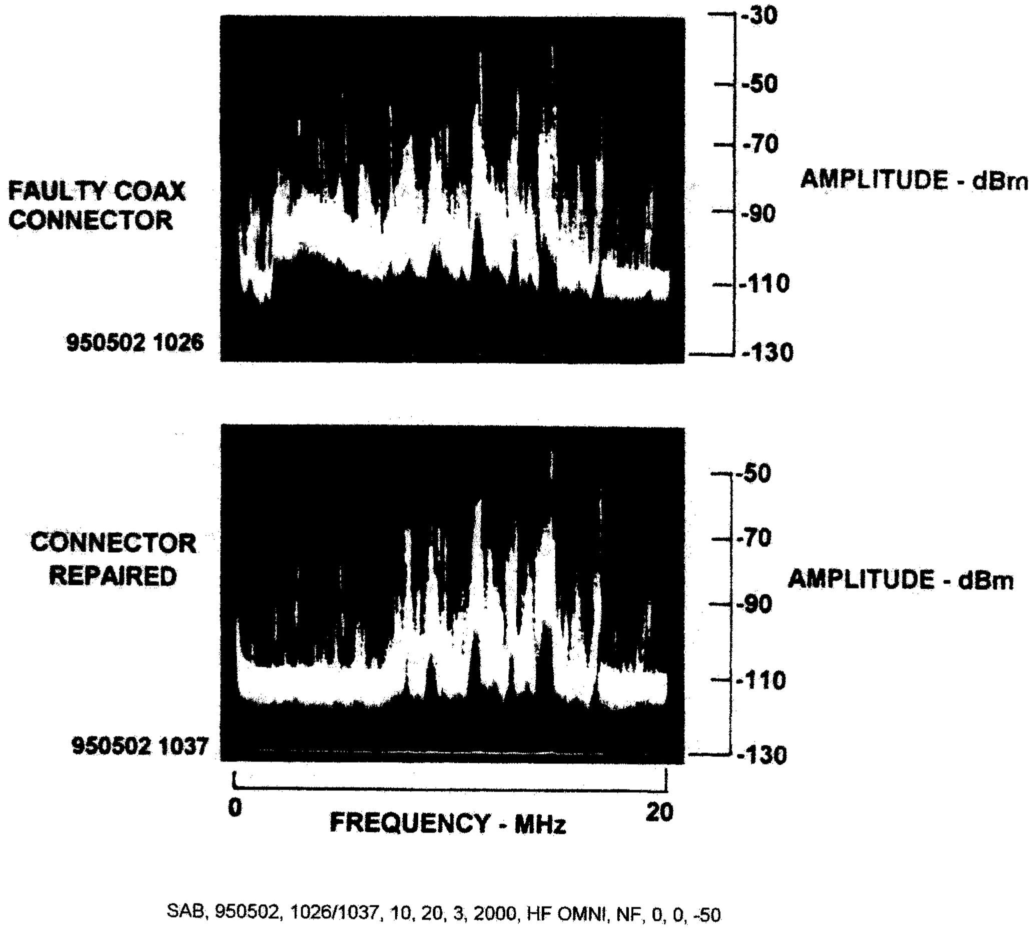


Figure 12 Impact of Improperly Assembled Coaxial Connector on Noise Level

5.4 Antenna Issues

A number of sources of radio-interference and radio-noise related to antenna construction or antenna field issues have been identified. Examples are provided to illustrate some typical problems.

Experience has shown that welding on galvanized metal after galvanizing produces nonlinear joints. Welding prior to galvanizing does not normally produce nonlinear junctions.

A single alternating-frequency current conducted through a welded joint on galvanized metal will result in the production of harmonics. Current from multiple signals flowing through a non-linear joint will result in the production of intermodulation products and intermodulation noise as well as harmonics. Such sources can inject massive numbers of spectral components of current and voltage into the tower structure where the tower structure is physically close to its receiving antennas. This current and voltage can be coupled into the nearby receiving antennas, resulting in unwanted noise and interference being fed to all receivers connected to the antennas.

Figure 13 shows an example of a weld on a galvanized portion of an antenna tower at a receiving site. This tower was located on a hilltop receiving site in direct line of sight to television, FM, and AM broadcast transmitters as well as being close to other commercial and military communication sites. Such sources injected significant levels of current and voltage into the tower and its associated cable shields. If nonlinear joints are present on such structures, intermodulation products and broadband intermodulation noise sources will exist.

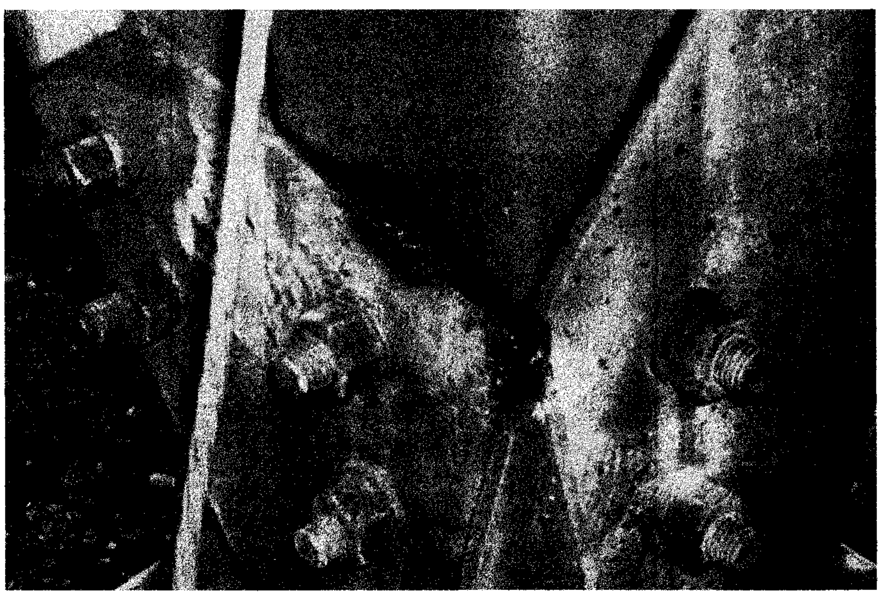


Figure 13 Weld on Galvanized Metal of a Receiving Antenna Tower

Figure 14 shows a ground conductor welded to a galvanized metal component of a tower at a receiving site. This tower was adjacent to the tower shown in the previous figure. The weld was clearly of poor quality, and it was necessary to use a tie wire to maintain its mechanical properties. In addition to its ability to produce intermodulation products and broadband intermodulation noise, the poorly welded joint would be blown free of the tower from surge current induced by a lightning strike.

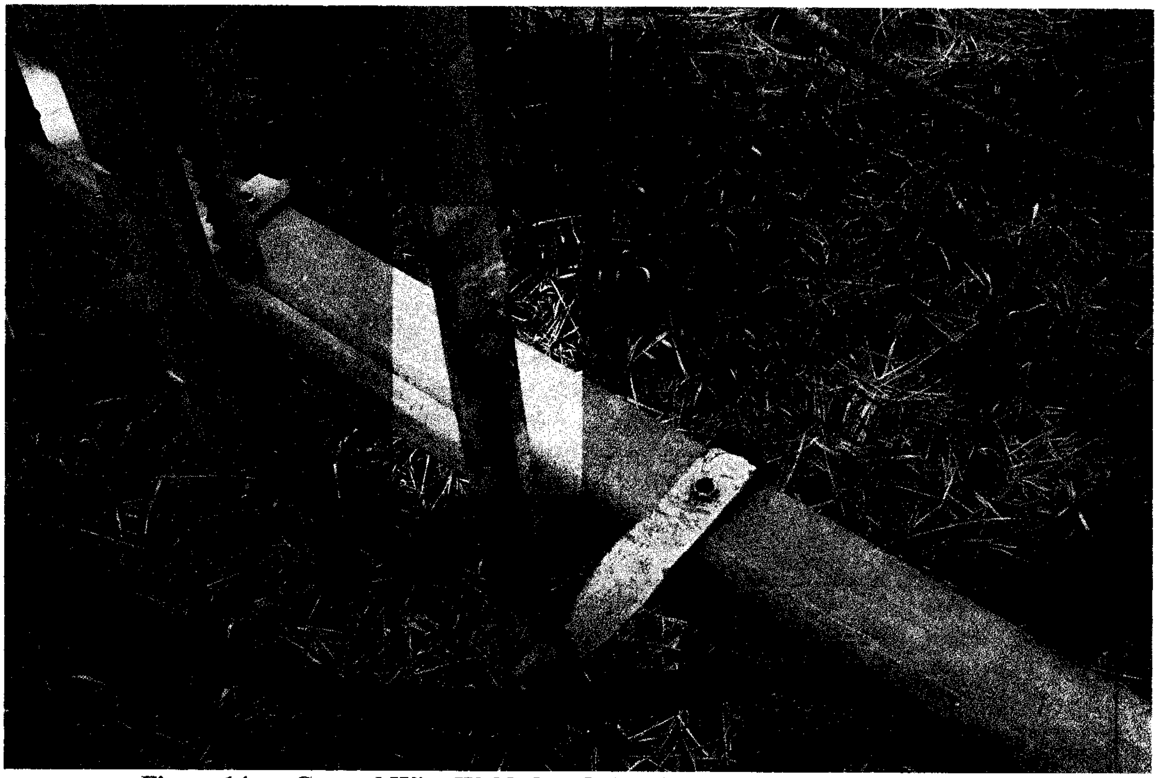


Figure 14 Ground Wire Welded to Galvanized Metal on Antenna Tower

The solution to the ground cable connection is to use a standard electrical compression fitting on the ground conductor and bolt the fitting to the tower. All other tower fittings should be bolted.

Welding on the galvanized metal components of a receiving or transmitting antenna tower should be prohibited.

Impurities in a CADWELD® can also produce nonlinear joints which can be a source of harmonics, intermodulation products and broadband intermodulation noise. Figure 15 shows an example of a CADWELD® that connects an antenna counterpoise wire to a ground stake. A large number of such welds existed in the ground plane for the antenna.

The use of mechanical electrical fittings fabricated of bronze will eliminate the possibility of these connections being sources of low-level intermodulation products and noise in the antenna counterpoise system. This will also eliminate the high levels of intermodulation when nearby radio transmitters are operated. CADWELD® joints should not be used on or near antenna fields or at any other location within or near a receiving site.

Figure 15 CADWELD® on Antenna Counterpoise Wire

The rusty joint effect is well known to old-time radio engineers, especially when the rusty joint is in the antenna system. Figure 16 shows an example of such a joint that was part of an antenna guy. Also of concern is the use of chain in the guy because its joints can move from wind resulting in intermittent contacts. A thin layer of insulating oxide is formed on galvanized metal, and wear from movement can intermittently make and break through the layer. Non-conducting line should be used for all antenna guy material or metallic guys with properly installed and spaced compression insulators.

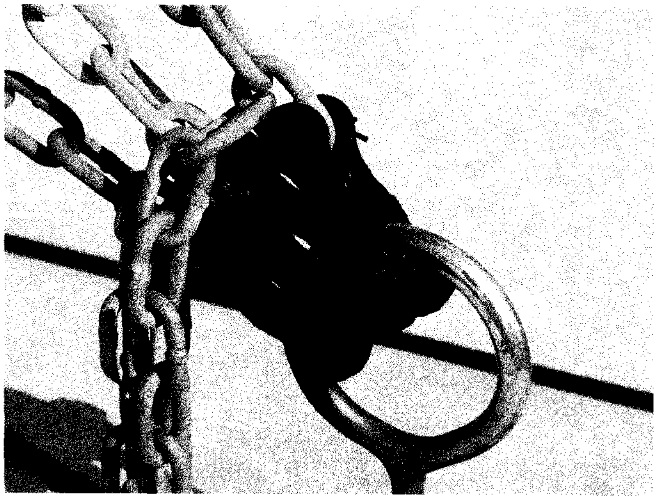


Figure 16 Example of a Rusty Joint

Figure 17 shows an example of multiple incidental contacts between conductors where the conductors are physically and electrically close to receiving antennas. Low-level standing waves of current and voltage exist on such conductors from ambient radio signals. The intermittent contacts formed by minor movement of the conductors result in impulses due to small potential differences between the conductors. These low level impulses radiate and result in low-level and erratic impulsive noise at the input of the site's receivers.

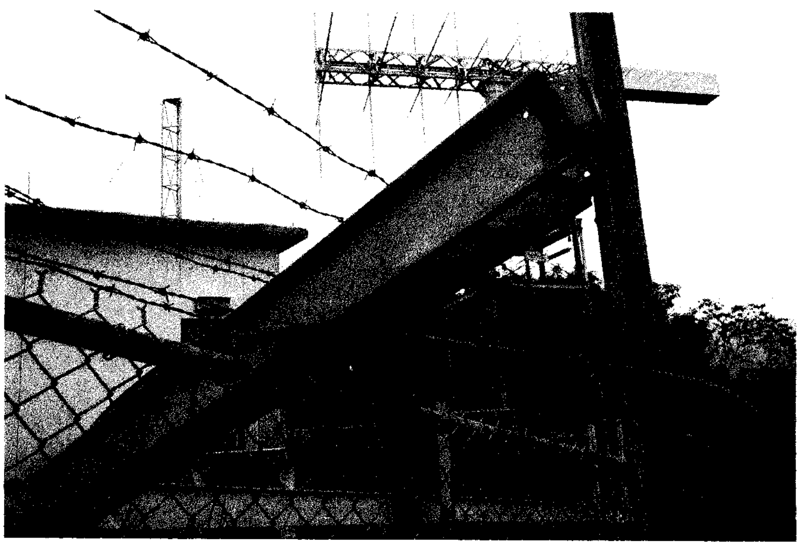


Figure 17 Example of Incidental Contacts